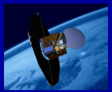
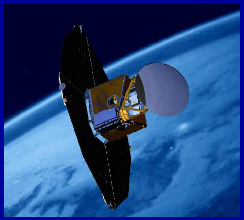
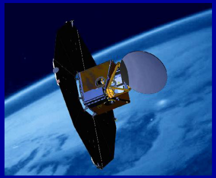
Exploratory SPace Submm Radio Interferometri Telescope

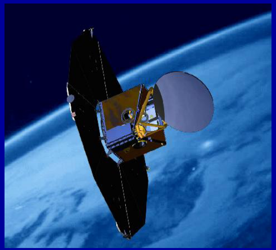
Hubble resolution in the FIR

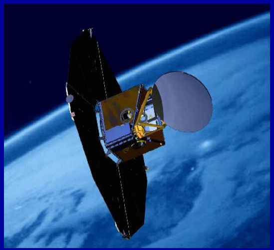


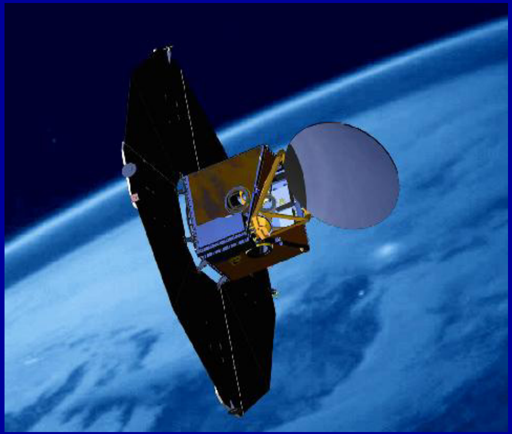


Th. de Graauw, J. Cernicharo, A. Bos, J. Bregman, L.Darcio, J-W den Herder, A. Gunst, F. Helmich, P. Maat, J, Noordam, A. Quirrenbach, P. Roelfsema, L. Venema, P. Wesselius, W. Wild, J. Martin-Pintado, P. Yagoubov, et al.









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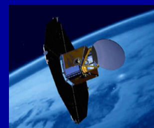
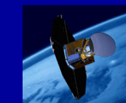
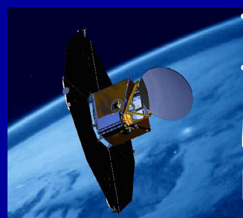
ESPRIT

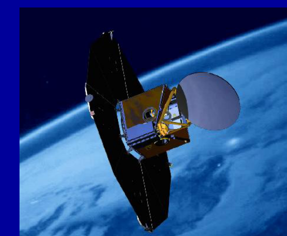
Main Charateristics of Mission under study

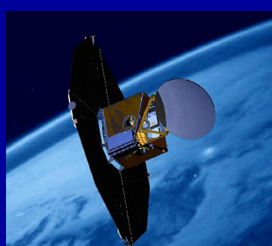


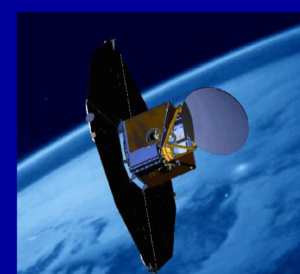


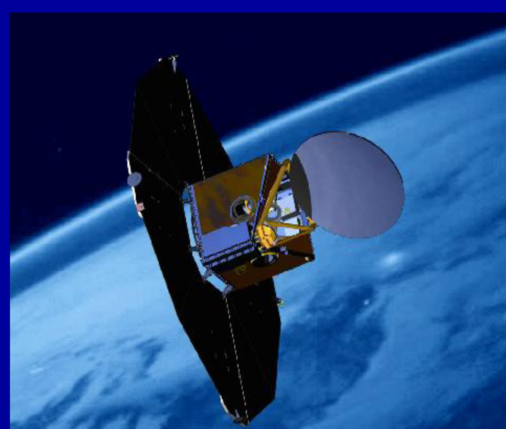


Telescopes : N >6 ; free-flying
Telescope size : ~ >3.5 m
Temperature : ambient (90K)
Proj. Baselines : ~ 7- 200-1000 m
Freq. ranges in 1.5–6 THz (200-50 μm)
Angular Res.: 0.02 arcsec (@100 μm)
Spectr. Res.: 1 Km/s (@100 μm)









Outline:

- 1. Background and context: Baseline Concept
- 2. Pros and cons of heterodyne systems for FIR interferometry in space
- 3. Science objectives
- 3. Front-ends: status mixer and LO technology, IF amp
- 4. Delay line and Correlator considerations
- 5. Metrology and configurations
- 6. Sensitivity
- 7. Study Plans

Heterodyne- versus Direct-Detection Missions: Pros and Cons I

After Herschel:

• unlikely to have another mixed detection technique (direct and heterodyne) mission due to *<u>increase</u>* of technical requirements for both w.r.t. previous missions to meet new scientific capabilities

• *<u>Direct</u> detection requirements for* very low background levels:

1. Telescope temperature low level (<6K)
2. Instruments at low level (2 K)
3. Detectors at very low level (< .1 K)
4. Telescope/structure/instruments under very strict stray-light requirements

• Sensitivity of direct detectors will (have to) be improved by 2 – 3 orders of magnitude

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Heterodyne- versus Direct-Detection Missions: Pros and Cons II

<u>*Heterodyne detection (non)-requirements:*</u>

- Not background limited; Warm telescope/instrument is possible
  - Moderate cooling requirements:
    1. Telescope at ambient temperature
    2. ~4 K mixers; 15 K pre-amps;
    3. ambient temperature instruments
- Warm electronics (warm IF and back-end spectrometers) thermally stable
- Telescope design for low standing waves (>>off-axis)
- Additional:
- Heterodyne technique allows "infinite" signal copy/division at no cost
- For interferometry it allows post detection correlation
- Large number of elements does not affect SNR in correlation

In summary: "*<u>Separate" missions</u>* allow for optimized designs of satellite, telescope, and cooling resulting in simpler satellite system; longer lifetimes; optimised orbits, etc… It Must be investigated!
So more science capability/$-€.

Cooling Requirements with heterodyne receivers

- Heterodyne Receivers have moderate cryo-cooling requirements:
  1. Telescope at ambient temperature; in L2 orbit: ~80 K.
  2. ~4 K mixers; 15-20 K pre-amps, 50 K LO
  3. Ambient temperature instruments
- Cryo-cooler specifications for receiver with QCL:

Temp level	One receiver with 2 mixers and 1 LO. Dissipation is:	2 Receivers operating simultaneously at 2 Frequencies; Total of 2*4 mixers on-board. Dissipation is:
30-50 K	LO: 2.5 Watt	LO: 5 Watt
	Amps: 20 mW	Amps: 40 mW
20 K	2 Pre-amps: 16mW	4 pre-amps: 32 mW
4.5 K	2 mixers: 0.5 mW	4 mixers: 1 mW
	Parasitics: 1 mW	Parasitics 8 mW

` Warm electronics (warm IF and back-end spectrometers) thermally stable
- Experience shows required temperature slope < 1 K/hour.
- This puts requirements on the Service model thermal design

ESPRIT Basic Concept

<u>Mission Basic Concept:</u>

- Telescope sizes : ~ >3.5 meter ; off-axis
- Number of elements: N >6 ; free-flying
- Projected Baselines: ~ 7- 200- 1000 meter
- Freq. ranges/spots: in 1.5- -- 6 THz (200 – 50 μm)
- Spectral Resolution: 1 Km/s at 100 μm. (0.1 goal)

- F.O.V.: ~ 6"
- Pointing Requirements: - accuracy: 0.3"; - knowledge: 0.1"
- Spatial Resolution: 0.02" at 100 μm

- Image Dynamic range: 100
- Spectral Dynamic range: 1000

- Heterodyne Receivers wuth Tsys: 1000 K (N receiver bands; HEB mixers @ 5 K; dual polarisation; QCL as LO's)
- IF: > 4 GHz wide
- Correlator: 4 sections of 1 GHz, each 128 channels

- Baseline Configuration: scalable 3-D; quasi-chaotic

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Previous/On-going IR/Submm Missions with spectroscopic capabilities

Missions	Telescope Diameter in meters	Comments
IRTS	0.15	Observatory
ISO	0.6	Observatory
MSX-SPIRIT	0.34	"Survey"
HST-NICMOS	2.4	Instrument at HST
SWAS	0.6	Heterodyne Receivers
ODIN	1.1	Heterodyne Receivers
Spitzer	0.85	Observatory Just launched

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Future Submm/FIR Spectroscopy Missions

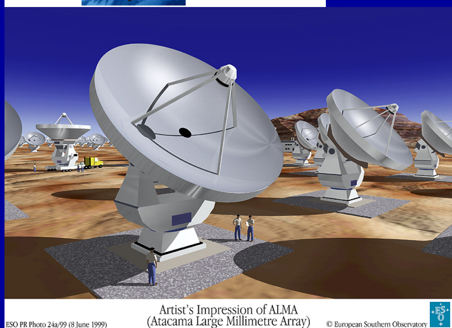
Telescope		Launch Year	Diameter
• ASTRO-F	(space; 2- 200 μm)	: 2004/5	0.7 m
• SOFIA	(airborne; 3- 300 μm);	: 2004	2.5 m
• APEX	(ground-based; 500-1200- GHz)	: 2004	12 m
• ASTE	(ground-based; 500-1200- GHz)	: 2004	10 m
• Antartica Tel.	(South Pole; 300- 3000GHz)	: 2005	10 m
• ALMA	(ground-based interf.; 50-900 GHz)	: 2008>	64x12 m
• Herschel	(space; 3.5 m; 60-600 μm)	: 2007	3.5 m
• JWST-MIRI	(space; 6 m; 5-30 μm in L2 orbit)	: 2011	6 m

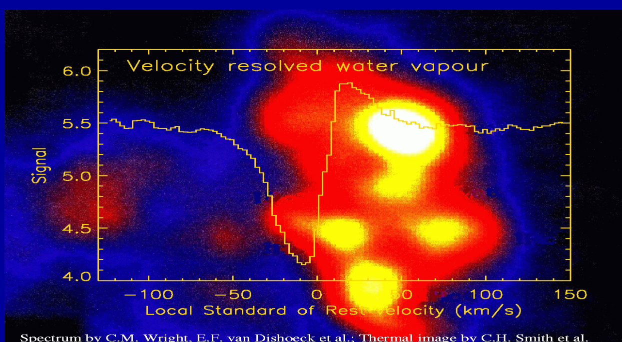
Relation to ALMA
What ALMA not can do:

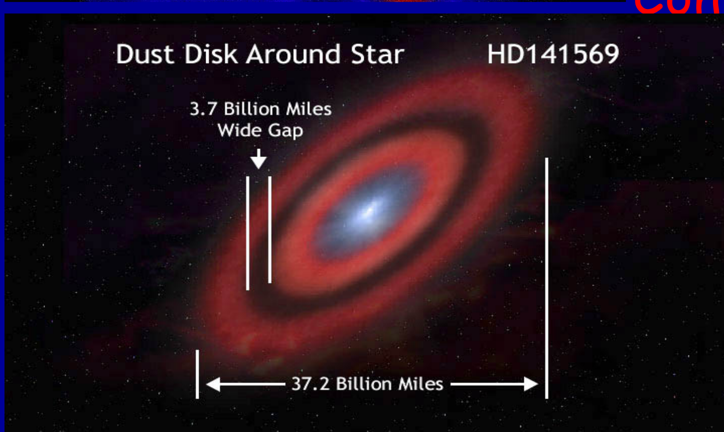
- ALMA will do most important science in all fields of Astrophysics,
  - However:
- limited to frequencies < 900 GHz
- limited to atmospheric windows

- WHAT ALMA PROBABLY WILL NOT DO ?
  - light molecular species with rotational transitions >900 GHz
- H_2O, OH, H_3O^+, HD, CH
- Star forming regions, protostellar disks
- Oxygen Chemistry in Protoplanetary disks,
- PDRs, Shocks
  - High excitation lines of CO, HCN, HCO^+, CN,…
- Shocks, PDRs, PPNs, PNs
- \- Atomic fine structure lines :: O[I], N^+, C^+
- PDRs, Shocks, Galaxies, AGNs, quasars…

Science with ESPRIT







<u>Science Objectives (See Cernicharo):</u>

A. Complementary to ALMA:

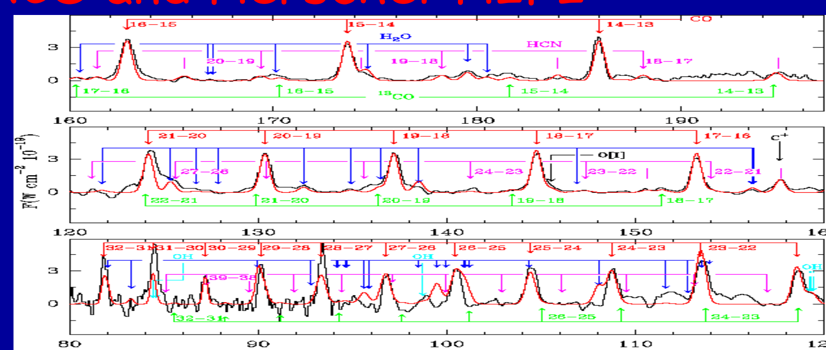
- Different frequency range > 900 GHz (ALMA)
- Atmosphere hindering in phase and transmission

B. Imaging **water** and molecular ions in star forming regions and proto-stellar/proto-planet disks
H2O, OH, OH+, CH, CH+, CH2+, CH3+,

C. Imaging in important atomic fine-structure lines: CII, NII, OI, OIII,
Imaging in high excitation lines of CO, HCN, HCO+, etc

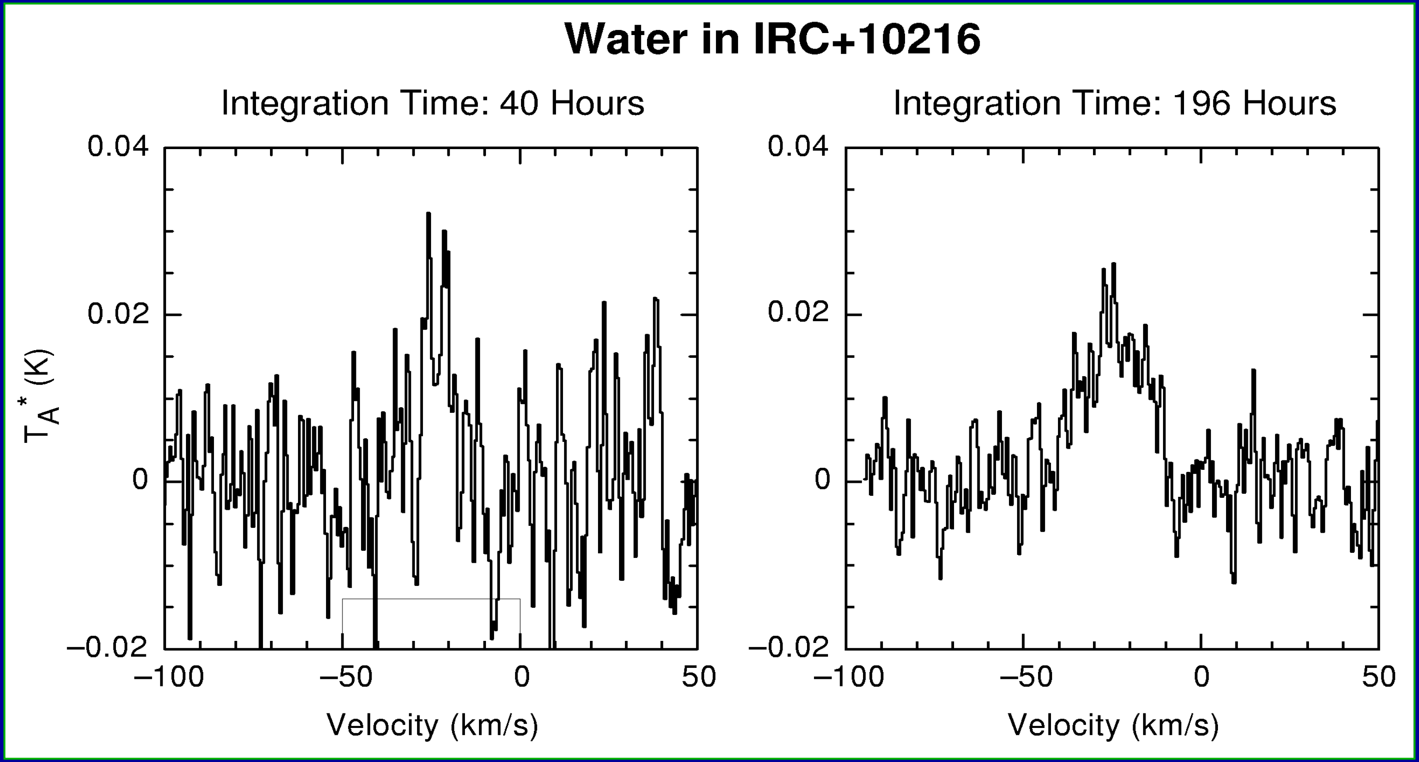
D. Follow-up on ISO-LWS, SWAS, ODIN.,

Confirmation of the science case by Herschel-PACS and Herschel-HIFI



SWAS detection of water vapor around the *carbon*-rich star IRC 10216 (Melnick et al.)

H2O abundance implied is ~ 10-6 Collection of orbiting icy bodies, as an analogue to the Solar System's Kuiper Belt, being vaporized by the large luminosity of the star. Required mass of water ice ~ ten Earth masses, comparable to the initial mass assumed for our Kuiper Belt. Models predict water abundance, H2O/H2, is ~ 10-12



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Space Heterodyne Interferometer Mission: Receivers: Mixers and LO's

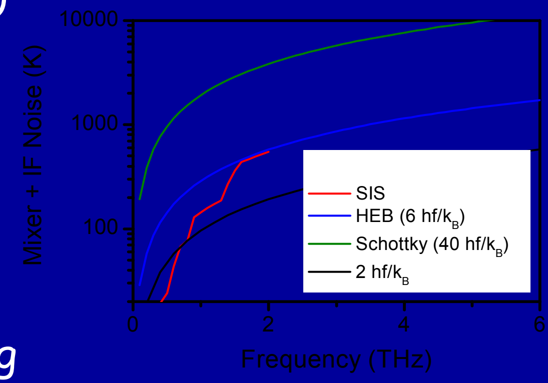
MIXERS:

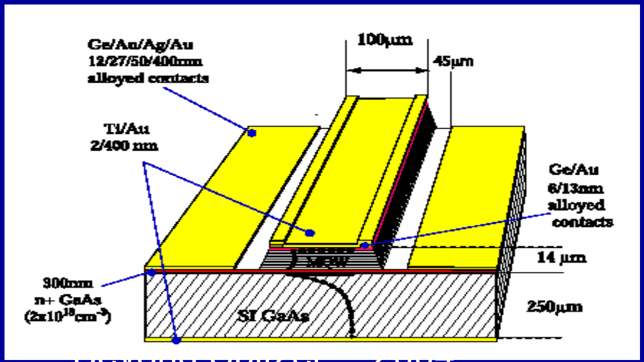
Recent Developments in Mixers show SIS mixers suitable up to 1.25 THz
Extension to 2 THz possible with new materials (NbN)

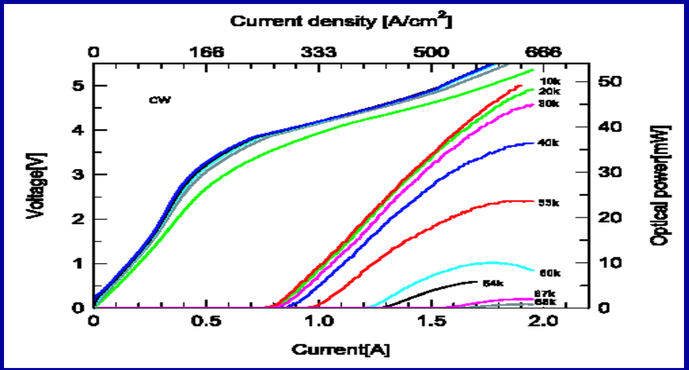
- HEB mixers suitable to 6 THz (?)
  Demonstrated up to 3.5 THz
- Superconducting Integrated Receivers (SIR) wityh FFO
  till 1.1 THz possible
- Alternative mixers being developed

•LO's:

- LO phase/frequency locking needed with LO phase referencing
- HIFI LO technology (Power amp with multiplier chain) can work to 2 THz
- Novel Quantum Cascade Lasers now demonstrated at 3.3, 2.7 and1.8 THz; can work from 6 THz down to 2 THz. Moderate development needed. An engineering job!







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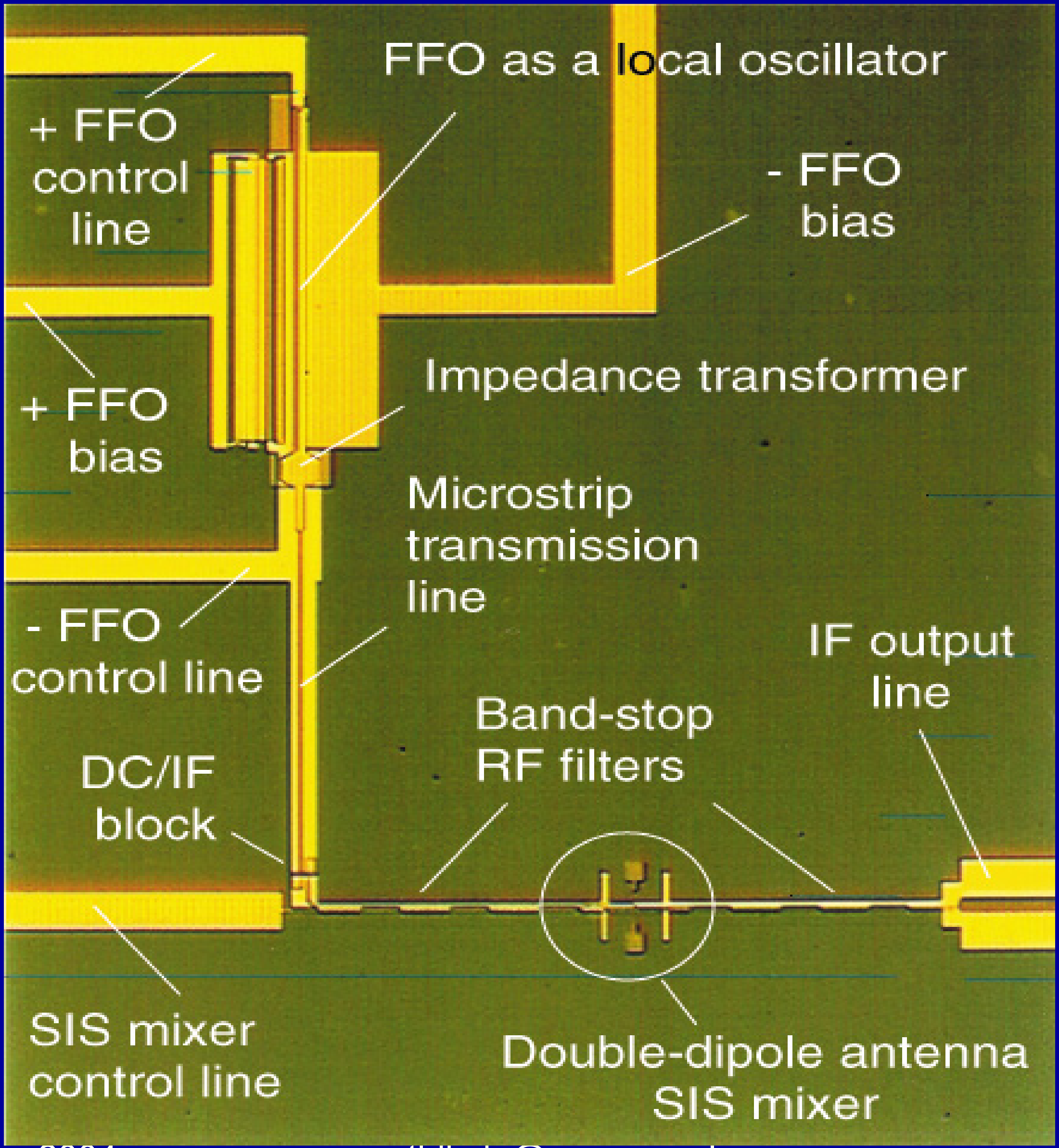
Superconducting Integrated Receiver (SIR) chip lay-out (Koshelets/Shitov)



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Delay lines and Correlators I

Delay Line Considerations:

- Long Coherence length ($\lambda_{coh}= \lambda^2/\Delta \lambda$) (30 m @ 100 μm) allows *delay line corrections in correlator software*
- Delay can be corrected by fine delay in clock and coarse delay after sampling
- Delay compensation requires (relaxed) knowledge of satellite locations
- Rate of change determines the metrology speed cycle
- Memory capacity required is small (about 7Kb per frequency band (1 out of 4))
- 12 bits address are sufficient

Correlator A/D Converter issues:

Under development for ALMA module of 3 bits at 4 GHz

- Total power dissipation (each signal channel) ~ 9 W
- Estimated power A/D module of 2-bit is 6 W

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Delay lines and Correlators II

Other Correlator Considerations:

- Number of lags
- Frequency/Spectral resolution
- Power dissipation

Another trade-off/choice to be made is to have either:

A. one correlator satellite station or
B. to have a distributed correlator, at each telescope/satellite element
   - distributed correlator minimises risk
   - allows for identical satellites with identical design
   - distribute the power needs for correlator
   - requires signal senders and receivers depending on correlator concept
     (combined with metrology system?)
   - attractive technique by "Optical Transport"

Metrology and Baseline Compensation Comparison with TPF and Darwin

1. Compared to TPF and Darwin orders of magnitude relaxed tolerance - From longer wavelength (10 μm–> 100 μm): 10 times
   - From higher spectral resolution (300→300.000) (1000 times)
   - Correlation length ($\lambda_{coh} = \lambda^2/\Delta\lambda$) about 30 m for resolution 1Km/s

Conclusion: metrology and delay setting is very easy as compared the Darwin/TPF requirements

2. Satellite elements metrology to:
- Establish the absolute interferometer baseline frame and its orientation (analog to setting a telescope dish)
- to set the correlation delays within fraction of correlation length

3. - Position metrology required between each telescope and at least three other telescopes
- knowledge of distance with accuracy in a few um range
- orientation knowledge necessary but coming from successive distance measurements

- Pointing accuracy: pointing at 0.3 arcsec accuracy; knowledge at 0.1 arcsec.

ESPRIT

Interferometer Metrology and Configuration

Note:

1\. Heterodyne technique allows “infinite” signal copy/division at no cost

2\. Interferometer configuration determines complexity of metrology system

3\. Detailed trade-off study is needed

3\. Scalable 3-D configuration seems to be most attractive:

- allows for very small baselines without danger for collision
- keeps metrology fairly simple
- trade-off to be made against u-v plane filling (coverage and speed)
- Complication by set-off of metrology components and telescope optical centre
- Metrology determines the amount of freedom in positioning the elements of the interferometer

Phase Calibration

Interferometer phase calibration is an important issue:

• Phase reference (point) objects in the telescope F.O.V., like in DARWIN, are not expected to be available
• There are no suitable (maser) point sources known in the FIR range.
• Fast switching between sources as planned for ALMA is impossible as slewing is slow and requires on-board resources
• Is a dedicated 90 GHz(SiO) or 180/325 GHz (Water) GHz channel required for phase calibration?

On the other hand:
• No atmosphere problems
• Telescopes in stable environment except thermal when re-orienting telescopes

Conclusion: a Space Heterodyne Interferometer has to rely on its metrology and self calibration

Space Heterodyne Interferometer Mission: Trade-offs: Number of elements--Diameter

- Number of interferometer elements and telescope diameters:

- Note: 3.5 m diameter gives ~10 m2; 8 m about 50 m2
- One 8m telescope with 5 times a 3.5m telescope?
- Gives a 10 times higher sensitivity compared to Herschel!

- Primary beam is relatively small: Use small focal plane arrays (3 times 3)? More cooling?

- Interferometer configuration versus metrology system complexity

- Etc..

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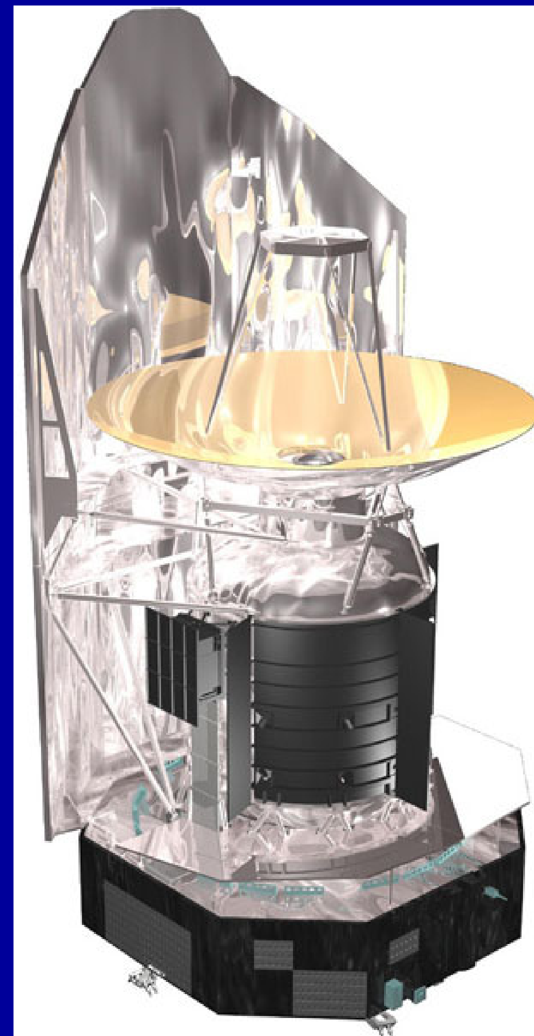
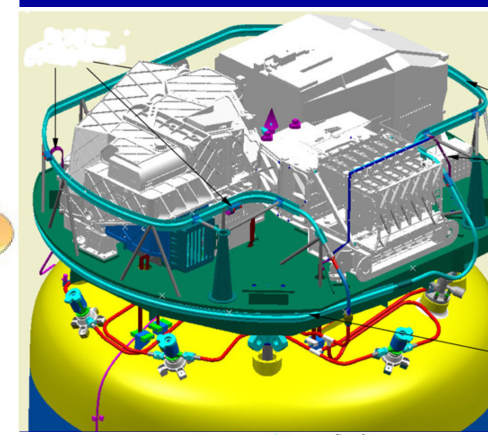
Preliminary Sensitivity Calculation for ESPRIT
6-elements (15 baselines)
3.5 m telescopes

Parameters:	Units	ALMA	Space Heter. FIR
Central Frequency	GHz	650	3000
Wavelength	Um	461	100
Velocity Resolution km/s	Km/s	1	1
Velocity Resolution MHz	MHz	2.2	10
Angular Resolution	arcsec	0.1	0.1
Baseline	m	900	200
Jy per K ratio	mJy/K	3.4	74
Tsys	K	1326	1000
Cont. flux density	mJy	0.13	16.7
Cont. Brightness	K	0.04	0.2
Line flux density	mJy	8.07	333
Line brightness	K	2.33	4.5
Integration Time (1 sigma)	secs	3600	3600

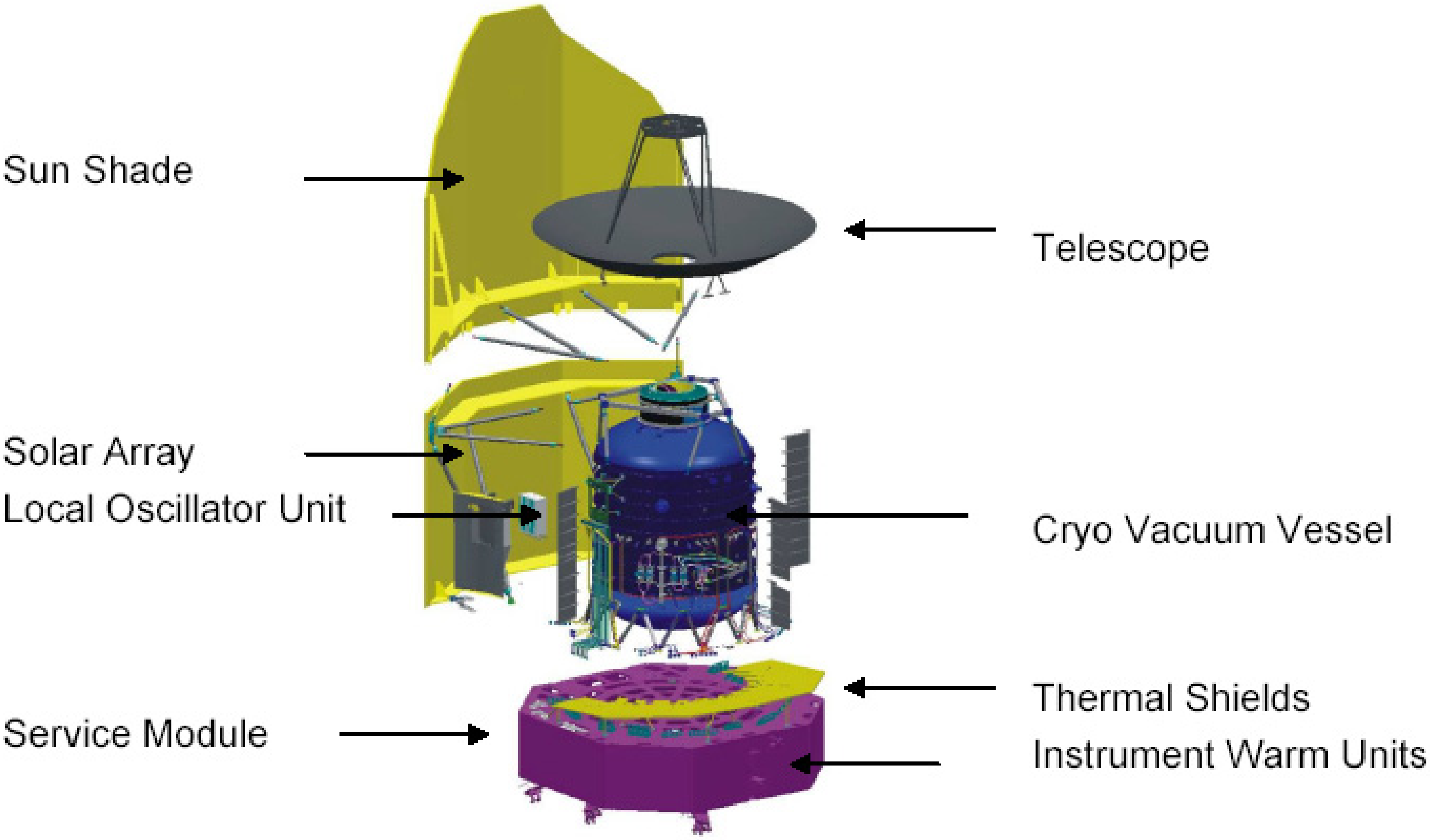
Herschel spacecraft

- telescope diameter 3.5 m
- telescope WFE < 6 μm
- telescope temp < 90 K
- telescope emissivity < 4%
- abs/rel pointg (68%) < 3.7” / 0.3”
- science instruments 3
- science data rate 130 kbps
- cryostat lifetime 4.0±0.4 years
- height / width ~ 7.5 / 4 m
- launch mass ~ 3200 kg
- power ~ 1500 W
- orbit ‘large’ Lissajous around L2
- solar aspect angle 60-120 deg
- launcher (w Planck) Ariane 5 ECA





Herschel spacecraft



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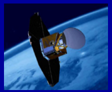
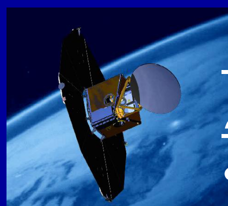
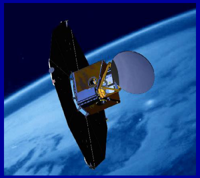


In Conclusion:



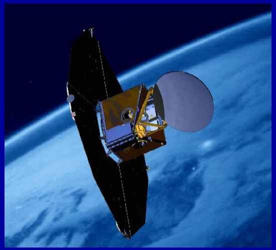


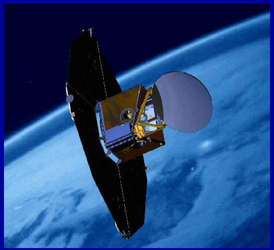
- *Science is compelling:*

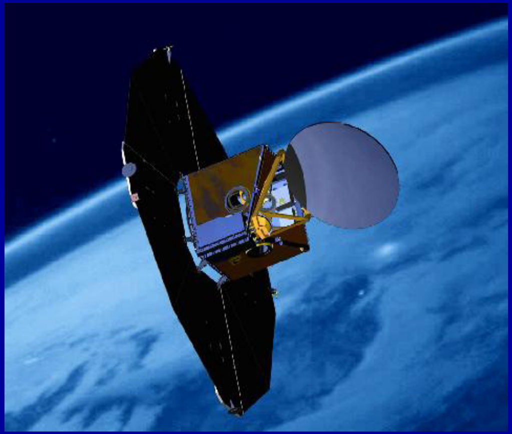
1. Observing how planets are formed;

2. Water the key molecule

- *Required detection/correlation technology exists and feasible*
- *ESPRIT could be an interferometry precursor for TPF, DARWIN, SPECS, etc.*







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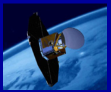
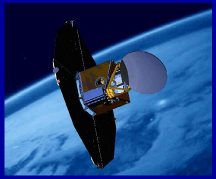
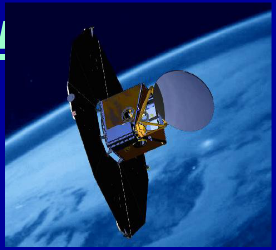
Exploratory SPace Submm Radio Interferometri Telescope

Lots of study to be done:

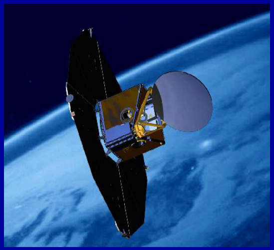


- Science Cases
- Front-end (LO, Mixers, IF)
- Correlator
- Metrology ; LO Locking
- Interferometer Configu





- Telescope
- Cooling
- System
- Etc.



Study team has now expanded with S. Guilloteau, J. Stutzki, U. Graf, H Langevelde, and already in team:
Th. de Graauw, J. Cernicharo, A. Bos,
J. Bregman, L.Darcio, J-W den Herder, A. Gunst, F. Helmich, P. Maat, J, Noordam, A. Quirrenbach, P. Roelfsema, L. Venema, P. Wesselius, W. Wild, J. Martin-Pintado, P. Yagoubov, et al.